Ground-based near-infrared imaging of the HD141569 circumstellar disk

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ABSTRACT

We present the first ground-based near-infrared image of the circumstellar disk around the post-Herbig Ae/Be star HD141569A initially detected with the HST. Observations were carried out in the near-IR ($2.2\,\mu$m) at the Palomar 200-inch telescope using the adaptive optics system PALAO. The main large scale asymmetric features of the disk are detected on our ground-based data. In addition, we measured that the surface brightness of the disk is slightly different than that derived by HST observations (at $1.1\,\mu$m and $1.6\,\mu$m). We interpret this possible color-effect in terms of dust properties and derive a minimal grain size of $0.6 \pm 0.2\mu$m for compact grains and a power law index for the grain size distribution smaller than -3. Basic dynamical considerations are consistent with the presence of a remnant amount of gas in the disk.

Subject headings: stars: circumstellar matter, stars: individual HD141569A, techniques: high angular resolution, techniques: image processing

1. Introduction

A circumstellar disk around the star HD141569A was detected independently by Augereau et al. (1999) and Weinberger et al. (1999) using the near-IR camera NICMOS2 on the HST. These first images revealed an optically thin annular disk with a complex morphology: 1/ an annular structure peaking at 325AU evidenced at $1.1\,\mu$m and $1.6\,\mu$m; 2/ a second axisymmetrical ring at 185AU unambiguously detected at $1.1\,\mu$m and less obvious in $1.6\,\mu$m images. More recent data obtained with STIS in the visible confirm the presence of two grain populations but also exhibit some strong asymmetries, especially in the closer annular pattern (arc-like patterns for instance), with an unprecedented angular

resolution (Mouillet et al. 2001). According to Mouillet et al. (2001), the anisotropic scattering of the light cannot account itself for asymmetric features and one has to invoke a non axisymmetrical distribution of dust very likely provided by the gravitationnal influence of pertubator(s) within the disk (an hypothetic planetary companion for instance), outside the disk (the two stellar companions lying at 7.54" and 8.93" from the star, 1065 AU and 1370 AU respectively if the companions are in the disk plane), or both. Some numerical simulations are ongoing to take into account the influence of the two T-Tauri like companions (Augereau et al., in preparation).
In addition, a close mid-IR emission previously inferred by spectral energy distribution fitting (Augereau et al. 1999) was detected within 100 AU (Fisher et al. 2000) with the Keck telescope at 10.8 μm and 18.2 μm. The complex environment of HD141569A clearly indicates that this star is in an evolved stage of evolution and may have already experienced a planetary formation stage.

We used the star HD141569A as a fiducial case to assess the capability of the adaptive optics system at the Palomar 200-inch telescope for detecting circumstellar disks around relatively young stars. Consequently, we report the first ground-based imaging of this disk in scattered light at near IR wavelengths. Despite a much lower sensitivity than the HST, our data feature a better angular resolution for identical wavelengths.

The observing sequence and the data reduction process are detailed in section 2 and the subsequent results are analysed in section 3. We discuss grains properties in section 4.

2. Observation and Data Reduction

Observations of HD1414569A (B9V, V=7.0, K=6.82, d=99pc) were carried out at the Palomar 200-inch telescope using PALAO the 241-actuators Adaptive Optics (AO) system installed at the Cassegrain focus (Troy et al. 2001) and PHARO the near IR camera (Hayward et al. 2001). The system can reach an averaged Strehl ratio of about 50% for bright stars ($m_v < 7$) under 1" seeing at near-IR wavelengths, and Strehl ratio as high as 68% have been obtained for very good seeing.

HD141569A was observed on May 9, 2001 with a Ks filter (2.2 μm) and a 25 mas/pixel plate scale. A coronagraphic Lyot mask (0.91" in diameter) was used to attenuate the diffraction pattern of the central star. In addition to the mask, an adequate cold Lyot stop undersizing the pupil is implemented inside the cryostat of the camera. This stop is mandatory to remove the unwanted starlight at the edges of the geometric pupil and to effectively improve the detection of faint circumstellar material. The coronagraphic PSF was calibrated in 4 sequences going back and forth between both the target star and an angularly close reference star of similar spectral type and magnitude (HD142864, A0V, V=7.2, K=7.2). The visible magnitude as well as the near-IR magnitude of this PSF calibrator are optimized to benefit from the same AO correction but also to obtain a similar signal to noise ratio in the IR images. Individual images of both the star and the reference were separately re-centered and finally coadded to provide an actual integration time of 1090s although the telescope time required to perform this thorough calibration amounts to about 2.5 hours. Although the target star was observed 10 minutes per sequence (including readout of the detector and sky calibration) it took about 5 to 10 minutes to repoint the telescope in order to accurately re-center the calibrator onto the mask. The average Strehl ratio was only 16% during the observation of HD141569 and was measured on the HD141569 companions (7.5" away).

At this point the circumstellar disk is not yet detectable and the extraction of faint circumstellar material relies on a specific reduction process. In order to compare our data with previous HST observations, we used the same data reduction technique described in

Augereau et al. (1999). First of all, the data for both the star and the PSF calibrator were reduced with standard procedure: bad pixels correction, flat field correction and sky subtraction. Then, before being subtracted the PSF calibrator need to be recentered and scaled in intensity with respect to the star. We estimate the scaling factor on the ratio of the target star image to that of the calibrator. As indicated in Augereau et al. (1999) the region ranges from 1" to 2" is relatively free of detected circumstellar dust and the ratio is almost constant for any orientation angle (Fig. 1). The global scaling factor is therefore estimated in this area and we adopt a value of 0.94 ± 0.02. The uncertainty on the scaling factor is derived from the pixel to pixel dispersion in the same annulus (see Fig. 1). The resulting subtracted images are shown on Fig. 2.

3. Data Analysis

After subtracting the calibrator, as explained hereabove, it is still difficult to disentangle between circumstellar material since diffraction residuals are dominating the signal around the mask. However, it was possible to unambiguously identify the circumstellar component by comparing our image with the ones obtained using the HST (especially with STIS). Then, to emphasize the disk the diffraction residue was cancelled out on Fig. 2. The global elliptical shape of the disk is outlined on Fig. 2b and several major features in agreement with HST images can be identified. The ratio between the major and the minor axis is 1.77 ± 0.15 corresponding to an inclination of $55.6^{\circ} \pm 3.5^{\circ}$ from pole-on assuming a circular disk (in agreement with Mouillet et al. 2001). Pieces of two independant rings are actually discernibles in the disk. The external ring is peaking at 325 AU and was initially detected by Augereau et al. (1999) and Weinberger et al. (1999). The inner ring is located at 185 AU but is slightly offset by 0.25" ($\approx 2.5\lambda/D$) to the West as already pointed out by Mouillet et al. (2001). It is however difficult to rely on this value since only 2 pieces of the inner ring are visible on our data and the fitting of an ellipse is somewhat uncertain. In addition, an extended emission detected with STIS is roughly visible to the North on Fig. 2 but the presence of the 2 companions as well as the brightness of the background strongly limit the detection in this area. The West part of the outer ring (ranging from about $PA = 225°$ to $PA = 310°$) is significantly dimmer than the Eastern region by about a factor of 2. This can be partly explained by a combination of the inclination of the disk with respect to the line of sight and anisotropic scattering properties of the dust grains. But the present data, like NICMOS2 and STIS images, exhibits some broken elliptical rings with strong azimuthal asymmetries (especially in the inner ring). Mouillet et al. (2001) concluded that a non axisymmetrical dust distribution was needed to account for the observed brightness asymmetries.

To obtain more quantitative comparisons with HST data the subtracted image was azimuthally averaged in several regions to derive the local surface brightness (SB) of the disk. First of all, the image was deprojected in order to average the pixels at the same physical distance from the star. The surface brightness displayed in mJy/arcsec^2 assumes K=6.99 for the central star (as measured in our Ks filter) and a 0 mag corresponding to a flux density of 667 Jy.

To evidence the asymmetries of the inner and the outer rings the surface brightness is plotted on Fig. 3 as a function of the position angle at respectively $r = 1.8$" and $r = 3.2$" where r denotes the distance from the star in the deprojected image of the disk. Taking I_{max} and I_{min} the maximal and minimal intensity of the azimuthal profiles presented on Fig. 3, the contrast is defined with the following relation:

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

The contrast is as large as 98% in the inner ring (1.8") between the bright North-east feature at $PA = 20°$ and the depleted South-east region at $PA = 130°$. The outer ring has a lower contrast of 71% between the Eastern part ($PA = 90°$) and the South-west region around $PA = 230°$.

Figure 4 compares the surface brightness of the disk in the Southern extension and in the South-Eastern extension where the outer ring is predominant compared to the inner one. The South-East part appears dimmer by a factor 1.49 ± 0.35 in the range 3" $\sim$ 3.5". This disk extension was totally or partially occulted by the wedge on STIS data and by spider diffraction spikes on NICMOS2 data. We also found a difference of surface brightness in the southern extension between our $2.2\,\mu$m data and the HST $1.6\,\mu$m data obtained by Augereau et al. (1999). The peak of the southern extension on HST image ($SB(1.6\,\mu\mathrm{m})$) is 1.33 ± 0.15 times brighter than in the K band ($SB(2.2\,\mu\mathrm{m})$) as measured on our data (assuming a scaling factor of 0.94). This difference is discussed in the next section in terms of scattering properties of the dust grains.

The surface brightness of the inner ring is best evidenced on Fig. 5. Although the position of the ring is in agreement with the HST data obtained by Weinberger et al. (1999) it remains difficult to compare the photometry since the HST image was actually averaged over 360° by Weinberger et al. to derive the surface brightness at $1.1\,\mu$m. But once our data are processed in the same way we find that the ring peaks at $0.116 \pm 0.030\,\mathrm{mJy/arcsec^2}$ compared to $0.270 \pm 0.020\,\mathrm{mJy/arcsec^2}$ obtained by Weinberger et al. (1999). The large amount of diffracted light at this angular separation is mostly responsible for the 25% uncertainty measured on the surface brightness at $2.2\,\mu$m.

4. Implications on disk and grains properties

4.1. A possible color-effect

Since the HD141569 disk is optically thin ($L_{\rm disk}/L_* = 8.4 \times 10^{-3}$, Zuckerman et al. 1995, see also subsection 4.2), the surface brightness wavelength dependence scales with the star flux $\Phi^*(\lambda)$ and the scattering cross-section averaged over the grain size distribution $\langle\sigma_{\rm sca}(\lambda)\rangle$. We then tried to investigate whether the observed differences of brightness between HST data and Palomar images are caused by the star flux only or reveal a color-effect of the grains. In the following we investigate the ratio:

$$\frac{\langle\sigma_{\rm sca}(\lambda_1)\rangle}{\langle\sigma_{\rm sca}(\lambda_2)\rangle} = \frac{SB(\lambda_1)/\Phi^*(\lambda_1)}{SB(\lambda_2)/\Phi^*(\lambda_2)} \tag{1}$$

with $\lambda_1 = 1.1\,\mu$m or $1.6\,\mu$m and $\lambda_2 = 2.2\,\mu$m. A deviation of this ratio from 1 reveals a non grey scattering behavior of the grains.

Assuming a B9V spectra for the star we found $\Phi^*(1.6\,\mu\text{m})/\Phi^*(2.2\,\mu\text{m}) = 1.656$. The uncertainty on the ratio $\langle\sigma_{\rm sca}(1.6\,\mu\text{m})\rangle/\langle\sigma_{\rm sca}(2.2\,\mu\text{m})\rangle$ at 3.2" is related to the surface brightness uncertainty as defined hereabove ($SB(1.6\mu\text{m})/SB(2.2\mu\text{m}) = 1.33 \pm 0.15$):

$$0.713 = \frac{1.33 - 0.15}{1.656} < \frac{\langle\sigma_{\rm sca}(1.6\mu\text{m})\rangle}{\langle\sigma_{\rm sca}(2.2\mu\text{m})\rangle} < \frac{1.33 + 0.15}{1.656} = 0.894 \tag{2}$$

These limits have been compared to numerical simulations in order to estimate the minimal size of the grains. We assumed first a collisional differential grain size distribution proportionnal to $a^{-\kappa}$ with $\kappa = 3.5$ and a minimum size $a_{\rm min}$ (e.g. Hellyer 1970). The use of this size distribution is justified by the short collision time-scales of the observed dust grains (see next paragraph). Figure 6 shows the theoretical ratio of the averaged scattering cross sections $\langle\sigma_{\rm sca}(1.6\,\mu\text{m})\rangle/\langle\sigma_{\rm sca}(2.2\mu\,\text{m})\rangle$ as a function of the minimal grain size $a_{\rm min}$ for three porosities $P = 0$, 0.5 and 0.95 and for typical chemical compositions. Although the lower limit (0.713) is unhelpful in that case, the upper limit (0.894) brings some constraints on the grain size distribution. In particular we found that the minimal size of compact grains ($P = 0$) is $a_{\rm min} \simeq 0.6 \pm 0.2\,\mu$m. This minimal size increases as the porosity and scales approximatively with $(1-P)^{-1}$: $a_{\rm min} \simeq 1.5 \pm 0.5\,\mu$m for $P = 0.5$, and $a_{\rm min} \simeq 16 \pm 9\,\mu$m for $P = 0.95$. However, in this calculation we used an averaged scaling factor of 0.94 and the grain size distribution is then no longer constrained if the scaling factor uncertainty is also considered (0.94 ± 0.2).

The same approach considering now the 1.1 μm HST data instead of the 1.6 μm measurements leads to :

$$0.576 < \frac{\langle \sigma_{\rm sca}(1.1\mu m)\rangle}{\langle \sigma_{\rm sca}(2.2\mu m)\rangle} < 1.135 \quad (3)$$

assuming $\Phi^*(1.1\,\mu{\rm m}\,)/\Phi^*(2.2\,\mu{\rm m}) = 2.970$. We then obtain: $a_{\rm min} \gtrsim 0.2 \times (1-P)^{-1}\,\mu$m, wich does not improve the accuracy but is in agreement with the analysis performed at 1.6 μm and 2.2 μm. The results are consistent with grains significantly larger than in the interstellar medium or in young massive circumstellar disks. Moreover, these values do not strongly depend on the assumed size distribution as long as κ is larger than 3. For small κ values, the scattering cross section is dominated by the large grains that tend to have a grey scattering behavior not consistent with the observed color-effect.

4.2. Basic dynamical considerations

Assuming circular orbits, we estimate an upper limit on the collision time-scale of the observed dust grains by the relation: $t_{\rm coll} \simeq (2\alpha\tau\Omega)^{-1}$ where $\Omega = \sqrt{GM_*/r^3}$ is the Keplerian circular rotation frequency, $M_* = 2.3\,M_\odot$ is the star mass (van den Ancker et al., 1998), τ the normal optical thickness of the disk in the near-IR at distance r and α a constant value depending on grains optical properties ranging typically between 0.5 and 1 in the regime of grain sizes considered here. Since the HD141569 disk is not seen edge-on and is most certainly not geometrically thick (Mouillet et al. 2001) an estimate of τ in the near-IR can be derived from the measured surface brightness $SB(r)$ with the simplified relation: $\tau(r) \simeq 8\pi r^2 SB(r)/\Phi^*(\lambda)$ (e.g. Appendix A in Augereau et al. 2001). At $2.2\,\mu$m we derive an upper limit for the outer ring of $\tau(3.2'') \simeq 3.4^{+0.2}_{-1.1} \times 10^{-2}$ (Southern direction) and $\tau(1.8'') \simeq 2.3^{+0.1}_{-0.8} \times 10^{-2}$ for the inner ring (N-NE direction). The positive uncertainty on $\tau(r)$ comes from the factor of 2 between the East and West part of the disk that can be due to anisotropic scattering properties of the grains whereas the above relation assumes grains scatter isotropically. This factor of 2 implies an upper limit on the asymmetry factor $|g|$ for the phase function of ~ 0.14 in a Henyey & Greenstein (1941) approach leading to a maximum deviation of $\sim 5\%$ from the isotropic case for scattering angles close to 90°. The negative uncertainty relies also on the optical properties of the grains since $\tau(r)$ can be at most a factor of 1.5 less if the minimum grain size of the size distribution is small compared to the wavelength and very porous (at least up to 95% of porosity). Coming back to collision time-scales, we obtain $t_{\rm coll}(3.2'')$ between 8.7×10^3 and 1.7×10^4 years and $t_{\rm coll}(1.8'')$ between 5.4×10^3 and 1.1×10^4 years, a few order of magnitude less than the star age (8 Myr)[1].

The survival of the smallest grains in the system needs then to be considered. Let us assume first that the disk is free of gas. In such a case, radiation pressure efficiently blow the smallest grains out of the system on very short time scales and the HD141569 outer system would then be of "debris-disk" type implying the presence of large bodies replenishing continuously the dust disk. Therefore, the grains observed in the near-IR and produced by collisions among large bodies are gravitationaly linked to the system if their radiation pressure to gravitational forces ratio is less than 0.5 (see e.g. Lecavelier 1998

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[1]Note that $(2\alpha\tau)^{-1}$ represents the typical number of orbits before a grain on a circular orbit undergoes a collision and the estimated time-scales correspond to 15 $\sim$ 30 orbits at 3.2" and 22 $\sim$ 44 orbits at 1.8"

and references therein.) Such dynamical considerations in a gas free environment give the following constraints on the minimum grain size in the HD141569 disk: $a_{\rm min} \gtrsim 6\,\mu$m if $P = 0$, $a_{\rm min} \gtrsim 9\,\mu$m if $P = 0.5$ and $a_{\rm min} \gtrsim 45\,\mu$m if $P = 0.95$. According to these results, bound grains in the HD141569 system should therefore induce fainter (or no) color-effect (Fig. 5) than observed. If the measured color-effect is realistic then grains smaller than the blow-out size limit in the absence of gas exist in the system. Given the CO J=2-1 brightness temperature measured by Zuckerman et al. (1995) implying a CO abundance significantly larger than for Main Sequence stars but faint compared to class II T Tauri stars, the assumption on the absence of gas is in fact probably not correct.

5. conclusion

HD141569 was used as a fiducial target to assess the capability of the 200-inch telescope in the search of circumstellar disk. The complex structure of the dusty disk (broken rings and rings offset by 0.25") has been successfully detected at near-IR wavelengths despite a modest Strehl ratio of only 16%. Therefore, this observation demonstrates the very good performance (comparable to that of the HST) of large ground-based telescopes equipped with high-order AO systems. Although a few circumstellar disks have been already imaged from the ground (β Pic or HR4796 for instance) in the near-IR, the 200-inch is to date the largest telescope equipped with a Lyot coronagraph, thus providing a large angular resolution ($\sim 90mas$ in K band) together with a high dynamic range. The result of a search for substellar companion has shown that under good atmospheric seeing, the detection threshold could be as large as $\Delta m \approx 9mag$ at 0.5", $\Delta m \approx 12mag$ at 1.5" and $\Delta m \approx 14 \sim 15mag$ beyond 2". This capability needs to be intensively exploited to further discover and characterize other circumstellar disks.

The many independant data obtain on HD141569 provided us with a multi-wavelength analysis (visible, near-IR and mid-IR) of this star, allowing to derive some physical properties of the grains contained in the disk. In addition to the successfull detection of the disk reported in this paper we have shown that a careful comparison of ground-based data and HST data obtained respectively at 1.6μm and 2.2μm could bring some contraints on the grain size distribution. In particular, we derive a minimal size of $0.6 \pm 0.2\mu m$ for compact grains and a grain size distribution steeper than a^{-3}. Grains are then larger than those found in circumstellar disks around pre-Main Sequence stars but also smaller than expected for a Vega-like system. Therefore, we conclude that gas is probably not fully dissipated in agreement with the CO detection by Zuckerman et al. (1995). However, as explained in section 3, the scaling factor between the target star and the calibrator star is the major source of uncertainty in that study. Once the scaling factor uncertainty and the porosity distribution are included in the anlaysis, we end up with a wide range of grain size.

More accurate results could be probably obtained if the data were obtained with only one instrument. In that respect, the new generation of Lyot coronagraphs becoming available on both the Keck telescope and on the VLT would be certainly helpful for the study of circumstellar disks.

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Fig. 1.— Azimuthally averaged profile of the ratio of the target star image to that of the calibrator obtained in 4 different regions (PA = 130°, 234°, 174° and 135°). The error bars represent the azimuthal intensity dispersion inside each regions. The scaling factor is estimated between 1" and 2" from the central star for which the ratio is almost constant and yields a value of 0.94 ± 0.02.

Fig. 2.— Final image of HD141569 subtracted with a reference star (a/) and deprojected (b/) assuming an inclination of 55°. Images c/ and d/ show the subtraction with a different scaling factor 0.92 and 0.96 respectively $+1\sigma$ and -1σ from the averaged value R=0.94 (a/). Two circles are overplotted on the sub-frame b/ to evidence the inner and outer rings. The very bright area at the upper-right corner and the diffraction spikes are provided by the T Tauri companions.

Fig. 3.— Variation of the surface brightness across the inner ring (top) and the outer ring (bottom) as a function of the Position Angle. The contrast of the asymetries is as large as 98% in the inner ring and 71% in the outer ring.

Fig. 4.— Surface brightness profile of the Southern region ($PA = 180° \pm 10°$) and the South-East region ($PA = 130° \pm 10°$) compared to the surface brightness of the disk obtained with NICMOS at 1.1μm (Weinberger et al. 1999) and at 1.6μm (Augereau et al. 1999). The captioned image shows the azimuthally averaged regions around the star. The brightness profile at 1.1μm is a rough estimation of the Fig. 2 displayed in Weinberger et al. (1999). The profile at 1.6μm is obtained with real data obtained by Augereau et al. (1999).

Fig. 5.— Surface brightness profile of the North-East region ($PA = 18° \pm 10°$) and the South-West region ($PA = 215° \pm 10°$) compared to the surface brightness of the disk obtained with NICMOS at 1.1μm (Weinberger et al. 1999) and at 1.6μm (Augereau et al. 1999). The captioned image shows the azimuthally averaged regions around the star. The brightness profile at 1.1μm is a rough estimation of the Fig. 2 displayed in Weinberger et al. (1999). The profile at 1.6μm is obtained with real data obtained by Augereau et al. (1999).

Fig. 6.— Numerical simulations of the theoretical ratios $\langle\sigma_{\rm sca}(1.1\,\mu{\rm m})\rangle/\langle\sigma_{\rm sca}(2.2\,\mu{\rm m})\rangle$ and $\langle\sigma_{\rm sca}(1.6\,\mu{\rm m})\rangle/\langle\sigma_{\rm sca}(2.2\,\mu{\rm m})\rangle$ as a function of the minimal grain size $a_{\rm min}$, for three porosities $P=0$, $P=0.5$ and $P=0.95$ and assuming a grain size distribution following a -3.5 power law. The following chemical compositions have been assumed : graphite, amorphous and crystalline silicates for $P=0, 0.5, 0.95$, mixed with organic refractories and/or water ice (10% of the vaccum due to porosity) for non compact grains ($P=0.5, 0.95$). The upper and lower limits derived from Eq. 2 and Eq. 3 are also overplotted.